THE EFFECT OF THE TIBIAL SURFACE CONTOURS ON THE ROTARY STABILITY OF THE KNEE JOINT

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THE EFFECT OF THE TIBIAL SURFACE
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OF THE KNEE JOINT

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SUMMARY

The ability of the knee joint to resist displacement is most commonly termed the "stability" of the joint. This displacement may be axial, tangential or rotatory. The rotary stability is then the ability of the knee joint to resist rotational displacement. The problem of rotational stability is of research interest due to the nature of knee injuries which are sustained by football and basketball players, skaters and other sports participants, in industry and in the home.

The research work concerning rotatory stability has been centered for the most part on the influence of the soft tissue. The ligaments in the knee have been studied in great detail. While these structures are important the surface geometry influence, no less important, has been sorely neglected.

In this thesis the surface geometry of the articulating surfaces in the knee joint are studied in detail. The method is to precisely determine the surface contours of the distal femoral and proximal tibial surfaces; and then estimate the effects of tibial rotation on the femur due to contact pressure. The latter is accomplished by numerically modeling the surface contours using a digital computer. With the results of the surface contour determination and the computer

simulation it was concluded that the surface contours do influence the stability of the joint by influencing the tension in the collateral ligaments. More specifically external rotation tends to reduce the tension in the collateral ligaments and internal tends to increase it. This is because the femoral condyles move in grooves of ascending elevation on the tibial condyles during internal rotation; and in grooves of descending elevation during external rotation.

CHAPTER I

INTRODUCTION

The Problem of Abnormal Knee Joint Performance

Bio-mechanical research on the human knee has been stimulated by the general desire to acquire more information about the human body and by at least two clinical problems seen by medical practitioners: injury, that can occur in all competitive levels of sports, in industry and the home; and degenerative joint disease affecting the knee due either to a specific disease of the knee or simply to aging. The resulting effect on the knee is differently timed stages of the very same problem, an abnormal knee joint performance.

When an acute knee injury occurs, a corrective procedure is employed to reduce the symptoms. This procedure may involve as little as immobilizing the joint or as much as surgery. After the healing action is completed the joint performance still may not return to normal. The abnormal knee performance, now observed in the healed knee, may resemble that of a knee with degenerative joint disease. This reduced performance is usually associated with specific sets of symptoms and leads of clinically significant problems.

The major aspect of an investigation of the problem of abnormal knee joint performance concerns the stability of the knee. The stability of the joint is considered to be the ability of the joint to resist displacement. This displacement may be axial, tangential or rotary. In stability studies a reoccurring concern is the nature of the soft tissue influence (i.e. the ligaments, menisci, etc.) on stability. This has led to detailed studies on the functions of the ligaments in the joint. Most studies, however, have been done on the collateral ligaments that lie parallel to the leg on the inside (medial) and outside (lateral) of the joint. This is due to the fact that the cruciates, a pair of ligaments that lie somewhat horizontally between the two surfaces of the joints, are nearly inaccessible. Additionally the function of the cruciates is more or less implied by their placement. The length patterns of the collateral ligaments have been estimated, and these have been individually severed to study the changes in joint performance. The forces transmitted through the joint have been studied both with living subjects and with cadaver specimens. In yet another study the load bearing area in preserved joints were estimated.

Limitations of these studies have been:

(1) That the joints were commonly studied in abnormal positions where injury seldom occurs, such as full extension, and

(2) The influence of surface geometry was not considered.

The omission of detailed influence of the surface geometries is glaring but understandable because of their complexity and variety. The assumption, either implied or stated, that the geometric influence is small needs to be critically examined.

Statement of the Thesis Problem

Rotational stability is an important subset of the overall stability problem in that many injuries to the knee occur when joint rotation is present. The problem of the rotational stability of the knee joint is one of determining not only the influence of the ligaments but also of several other factors that may independently influence the ligaments. It is proposed in this thesis to experimentally verify the extent of the influence of the surface geometries of the articulating surfaces, either direct or indirect, on the rotational stability of the knee joint.

To achieve this the surface geometries are determined and modeled, the contact characteristics estimated and conclusions reached concerning this influence.

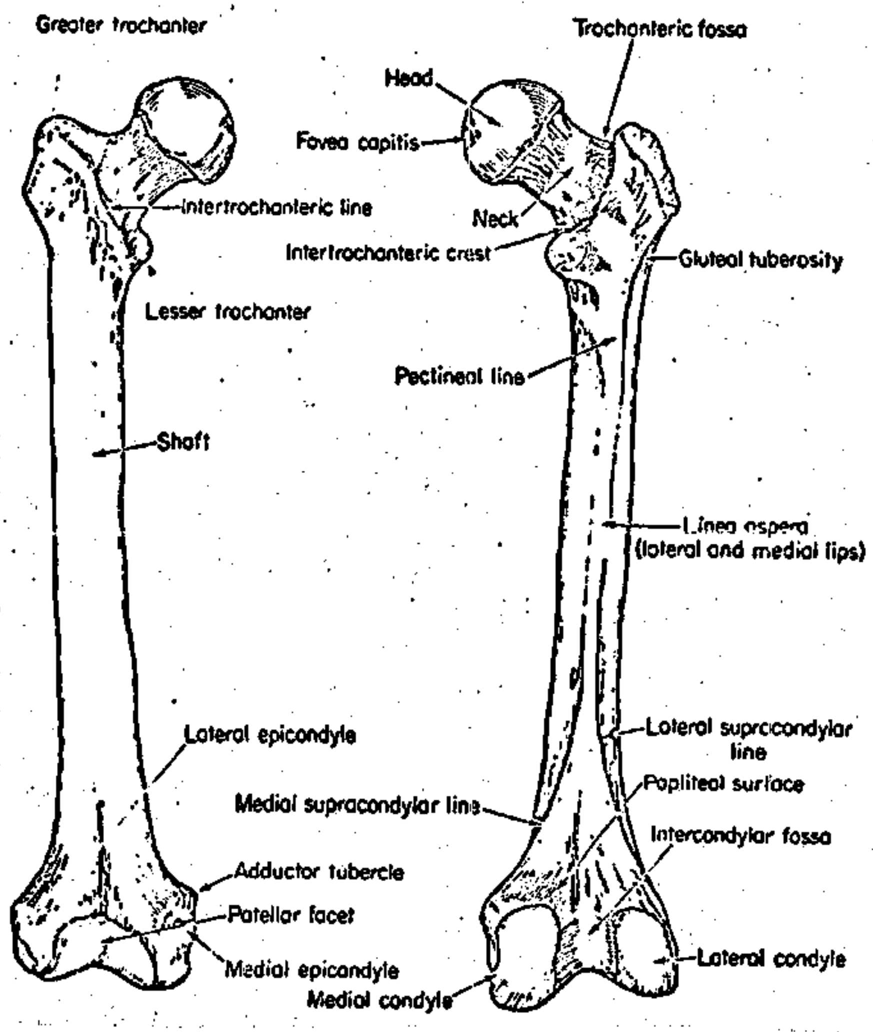
CHAPTER II

REVIEW OF PERTINENT LITERATURE

This chapter provides the necessary background of basic anatomy, histology and kinesiology needed to understand the rotational stability problem. Also included is a detailed review of previous research work both in biomechanics and lubrication, and a concluding section concerning injury mechanisms.

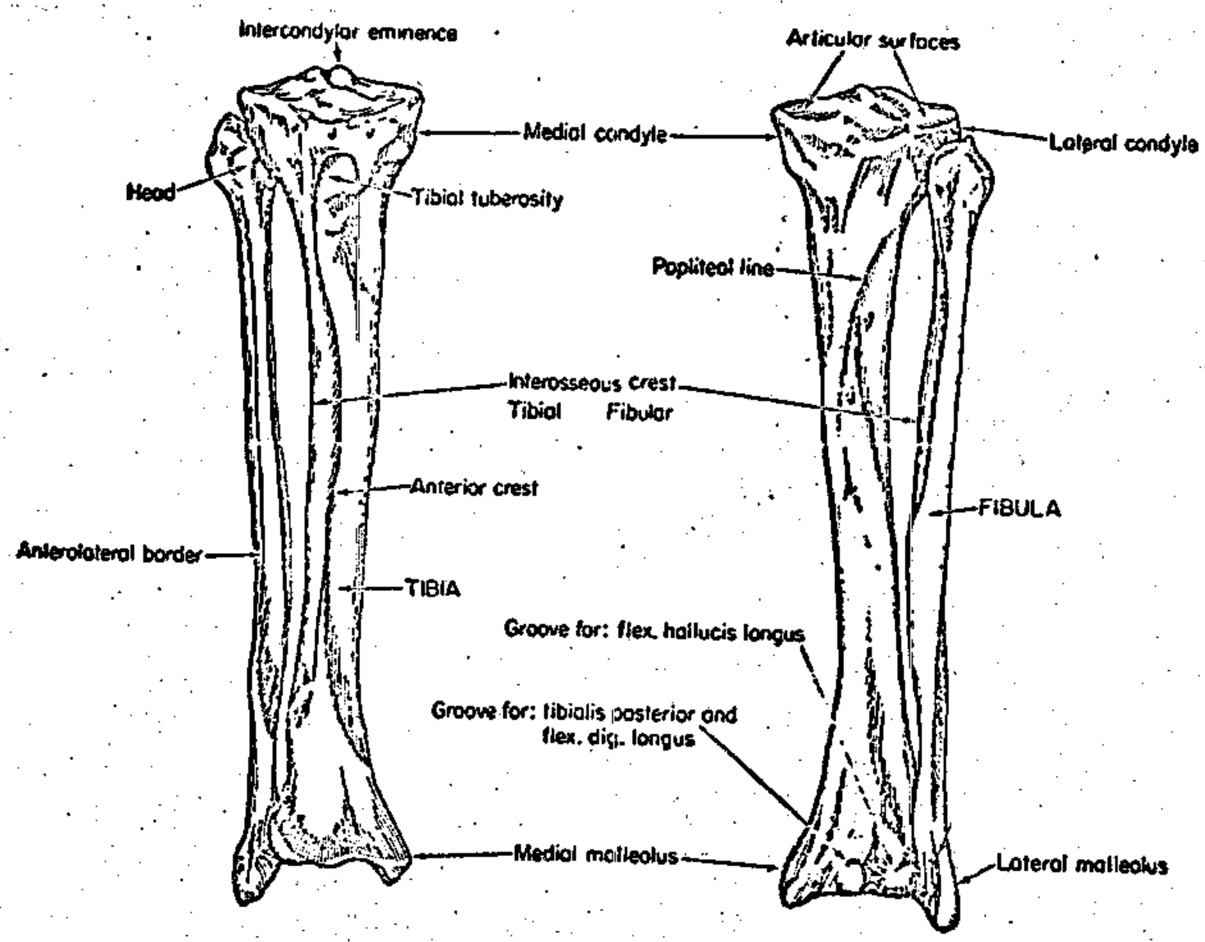
Anatomy

Anatomically, the knee provides the articulation between the tibia and femur which are the major bones of the upper and lower leg (Figure 1). The smaller bone in the lower leg, the fibula, lying laterally (to the outside) to the tibia does not participate in the articulation at the knee joint. The surfaces of the tibia and femur which are in contact are covered with a layer of tissue called articular cartilage and are lubricated by a thixatropic fluid called synovial fluid. The joint is enclosed by the articular capsule, an encircling band of fibrous tissue. Included in this capsule are ligaments which withstand stress and help to maintain the integrity of the joint. Also included in the capsule is the meniscus, a fibrous disk between the articulating surfaces. The cruciate and collateral ligaments



Femur (Kelley)

Figure 1. Tibia and Femur

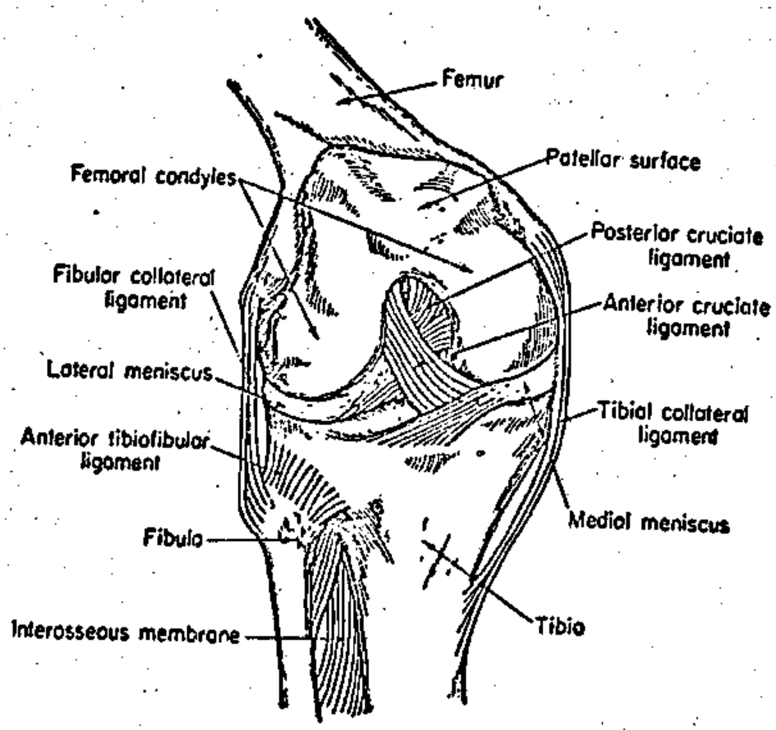


Tibia (Kelley)

Figure 1 (continued)

are described below in more detail because they are considered very important to the bio-mechanics of the knee joint [1].

The anterior cruciate ligament arises from the rough, non-articular tibial area. This is anterior to the inter-condylar eminence (tibial tubercle) and extends upward and backward (the knee in the anatomical position) to the posterior part of the medial aspect of the lateral femoral condyle. Figure 2, a right knee in dissection viewed anteriorly, illustrates this. The posterior cruciate ligament is directed upward and forward on the medial side of the anterior cruciate ligament. It extends from the area posterior to the tibial tubercle to the lateral side of the medial condyle of the femur. These ligaments prevent movement of the tibia forward or backward under the femoral condyles. The anterior cruciate prevents anterior displacement and the posterior cruciate prevents posterior displacement. The tibial collateral ligament is a strong flat band that extends from the tubercle on the medial condyle of the tibia to the medial surface of its shaft. Its length is eight and nine centimeters. The fibular collateral ligament is a rounded pencil-like cord about 5 centimeters long. It is attached to the tubercle on the lateral condyle of the femur above, and behind the groove for the popliteus muscle. It extends below on the lateral surface of the head of the fibula about one centimeter anterior to its apex [2].



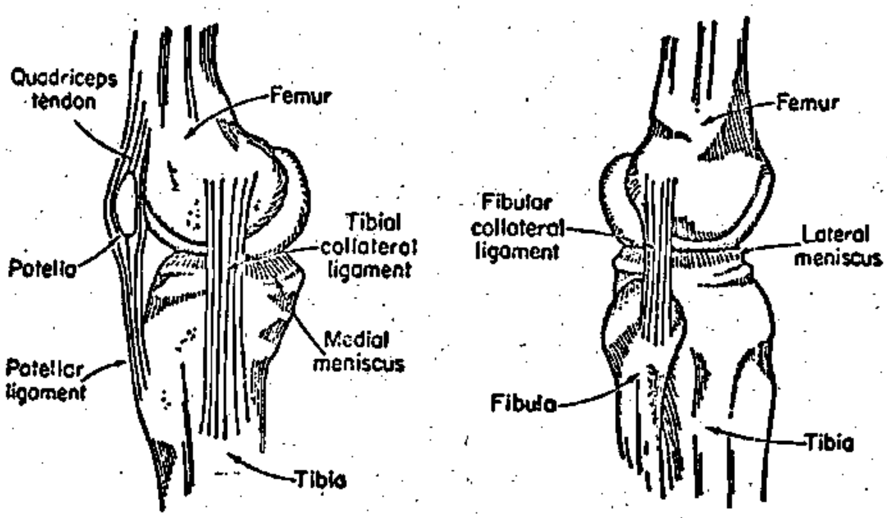


Figure 2. Soft Tissues of the Knee Joint (Kelley)

In the knee joint the synovial cavity (the area between the two surfaces) is divided by a disk of fibrocartilage called the meniscus. These pad-like rings serve to distribute but not bear the load on the articular surfaces during shock conditions and insure good contact between the articulating surfaces during movement. The medial meniscus is larger and nearly oval in outline. It is broad posteriorly and anteriorly thin and pointed. It attaches in the intercondylar area of the tibia in front of the anterior cruciate ligament. The lateral meniscus is more nearly circular and covers a somewhat greater proportion of the tibial surface than does the medial [2].

The mating surfaces of the tibia and femur are covered by articular cartilage. These surfaces are separated into a lateral portion and a medial portion called condyles. The condyles of the femur are rounded and convex. The condyles of the tibia have a more complex structure. Other sources have described the surfaces in the following manners (Fig. 3):

> The medial articular surface is oval and concave. The lateral surface, smaller and more circular, is concave from side to side and concavoconvex from before backwards; posteriorly it is prolonged downwards over the back of the condyle in relation to the popliteus tendon [3].

> The medial facet, oval in shape, is slightly concave from side to side, and backward. The lateral, nearly circular, is concave from side to side, but slightly convex from before backward, especially at its posterior part, where it is prolonged on to the posterior surface for a short distance [4].

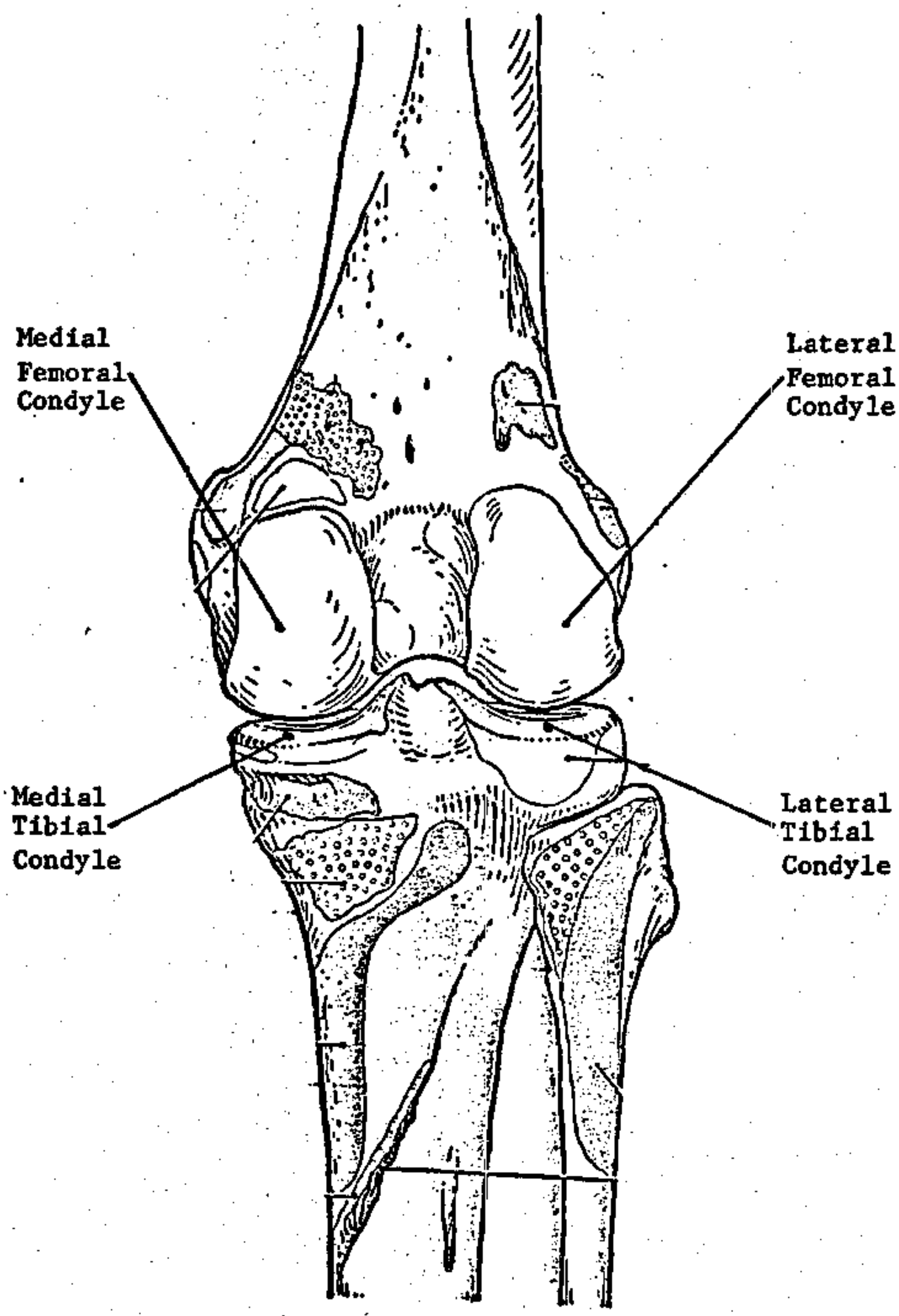


Figure 3. Bony Surfaces of the Knee Joint (Grant)
(Right Knee-Posterior View)

> The medial surface (facies medialis) is bounded by the medial and the anterior crest; it is broad superiorly, where it receives the insertions of the sartorius, gracilis and semitendinosus muscles; convex and subcutaneous in the remainder of its extent. The lateral surface (facies lateralis) lies between the anterior crest of the tibia and the interosseous crest. The proximal two-thirds presents a slight hollow, giving origin to the tibialis anterior muscle; the rest of the surface is convex and covered by the extensor tendons and the anterior tibial vessels [5].

In summary, the anatomy of the knee joint consists of the femoral condyles mating with the tibial condyles to form the articulating surface. The femoral condyles are convex but the tibial condyles have a much more complex geometry.

Histology

The structure of articular cartilage can most simply be described as a protein matrix comprised of water, collagen and chondroitin sulfate. Chondroitin sulfate is an organic compound with a molecular weight of about 40,000; the important association of protein to the chondroitin sulfate enables the articular cartilage to hold large quantities of water, sometimes up to 40 percent of the wet weight. This is important because protein chondroitin sulfate (PCS) with water is highly viscous. It makes the cartilage firm [6].

Articular cartilage is an example of hyaline cartilage, e.g., it contains no blood supply, innervation or lymphatics. The cartilage cells are arranged in three somewhat indistinct layers:

(1) A superficial layer in which the cells are flattened and small and are disposed with their long axes running parallel with the articular surface.

(2) An intermediate layer in which the cells are disposed in columns that run at right angles to the surface.

(3) A deep layer that is comprised of large cells [22].

The intercellular substance in the articular cartilage is a matrix of collagenic fibers suspended in a sulfated amorphous type of chondroitin sulfuric acid. This intercellular substance obscures the fiber network in young cartilage, but in older specimens it can be seen that the fiber bundles spread out becoming more parallel to the surface. This fiber network is the reason that the cartilage is so well suited to bear the changing stresses found in the joint. The collagen matrix gives the cartilage strength and the chondroitin sulfuric acid gives it resilience.

MacConaill [7] concludes that, "the ultimate structure of cartilage is essentially fibrous, as is that of bone; the difference between bone and cartilage lies in the impregnating substances." He also argues that the only function of the cells in the cartilage is to produce the fibers. Therefore cell protection by the fibers is of secondary importance. The fibers are collageneous, run obliquely between the articular surface and the bone and vary in density with the stresses on that part.

In summary, the articular cartilage is a collagen matrix with an amorphous intercellular substance. It is a firm bearing material for the joint.

Kinesiology

The movement patterns in the knee joint are only significant in the sagittal plane (forward and backward), with a range of about 127 degrees of flexion being the average. Resistance to hyperflexion (over flexion) is provided by the soft tissue behind the joint and to hyperextension (over extension) by the joint geometry and ligamentous structures. Rotation of the tibia about the long axis of the shaft is restricted to few degrees on the femur by the joint ligaments.

Although the knee is often considered a simple hinge, in reality, the joint action includes an amount of sliding during flexion. Smidt [8] studied x-ray data of 26 subjects to determine the instant centers of the tibia around the femur during flexion. He found that the mean locations of the instant centers, at seven different knee angles, are contained within a circle of diameter 2.3 centimeters and move through a pathway, during 90 degrees of flexion, of 3.2 centimeters in the level of the lateral femoral epicondyle. This illustrates the sliding during flexion. The knee joint then allows significant motion only in the sagittal plane. It allows a little axial rotation and sliding during extension.

Chronological Review of Biomechanical Studies

Some of the previous biomechanics work on the knee joint has been concerned with the forces transmitted through the joint. Expanding on the earlier work done by J. P. Paul [9], Morrison [10] used cinematography of subjects walking over a force plate. This measured the six component force actions. A generalized computer model interpreted the force plate data estimating the forces in three generalized muscle groups: quadriceps, femoris, gastrocnemius, and hamstrings. Further expansion of this work was done by Engin and Kordi [1], who used a cadaver with strain gages attached to the knee joint. This study attempted to determine the contact force on the medial and lateral plateau of the tibia for various normal and abnormal configurations.

Smidt [8] also measured the torque generated by the knee flexors and extensors by means of a force table and voluntary maximal efforts of 26 subjects. He used this data with x-ray data to conclude that the compression force in the tibial femoral joint during 90 degrees of flexion ranged from 0.42 to 3.4 times body weight.

Another subject of study was knee stability. Barham and Wooten [11] attribute the resistance of the knee joint displacement to two factors: anatomical and mechanical. The anatomical influences are separated into:

(1) the shape of the articular surfaces,

(2) the ligamentous structures,

(3) the viscosity of the synovial fluid,

(4) the atmospheric pressure,

(5) the fascial structures,

(6) the location and action of muscles.

These workers maintain that only lateral and medial stability is achieved by the collateral ligaments. This conclusion was reached by observing that most knee injuries damage the medial collateral ligament by either a direct blow from the lateral side or a severe inward twist. Also possible are tears to the medial meniscus. Less likely are lateral collateral ligament and lateral meniscus injuries from blows on the medial side.

The second most frequently injured ligaments are the cruciates. The anterior cruciate is strained when the knee is partially flexed and a force is applied across the back of the leg below the knee. A similar condition would result in the posterior cruciate when a force is applied across the front of the leg below the knee.

Barham and Wooten are in agreement with Horwitz [12], who came to the same conclusion writing 35 years earlier. The collateral ligaments are essential in providing the intrinsic stability of the knee making it into a rigid support. Furthermore these ligaments inhibit excessive rotation of the tibia upon the femur and in the absence of the cruciates they serve to inhibit excessive internal rotation.

Also in the absence of the cruciates the medial collateral ligament inhibits undue anteroposterior motion and the distraction of the tibia from the femur in flexion.

Horwitz continues that the cruciates are only "accessory" to the stability of the knee, or at least more prominent during the flexion phase of the knee joint motion. He concludes that the cruciates are "dispensible" to the stability of the joint, especially during weight bearing function. The dependence upon the cruciates for stability is small.

> The integrity of the knee joint is not markedly altered if the crucial (cruciate) ligaments alone are torn or excised, provided the collateral ligaments remain intact; that the tests usually considered indicative of cruciate ligament tear are evidence of collateral ligament injury as well; and that normal knee joint stability may be restored by the simpler repair of the internal collateral ligament injury alone, disregarding the associated cruciate ligament tear [12].

In another study by Brantigan and Voshell [13], approximately 100 knee joints were studied in an attempt to clarify the different functional roles of the ligaments in the knee joint. This was accomplished by viewing the ligaments intact; by cutting them and observing the resulting joint function; by planer studies on the joints; and finally by injecting the joint cavity and making frozen cross sections. It was concluded from this work that both collateral ligaments are taut in complete extension and that normal medial rotation of the tibia on the femur is controlled by the capsule, collateral ligaments and cruciate ligaments. In flexion the control is by the same structures minus the lateral collateral ligament.

Hughston [14] says that the posterior cruciate ligament should be considered the main stabilizer of the knee. It is his observation that only in rare cases is the knee functionally stable when the posterior cruciate ligament is torn and all other ligaments remain intact.

In a similar study Slocum and Larson [15] concluded:

> Rotatory instability is caused primarily by rupture of the medial capsular ligament and it occurs only when this anatomical lesion is present. However, the degree of joint laxity is increased when there are concomitant tears in the overlying tibial collateral ligament and increases yet further with accompanying tears of the anterior cruciate ligament.

Also of interest to the question of stability is the area of contact on the tibia and femur. Walker and Hajek [16] used a cement casting technique to determine this area. The areas were estimated by assuming the shapes to be elliptical and measuring the major and minor axes. They found that as flexion increased the contact on the tibial plateaus tended to move posteriorly. Evidence to indicate an internal rotation of the tibia on the femur from 0 to 15 degrees of flexion was also observed. The tibial spines functioned as one side of the contact area throughout flexion. The medial side contact area was generally about 30 percent larger than the lateral side with each side decreasing in size as flexion progressed. The geometry of the lateral tibial condyle was observed to contain both convex and concave portions implying that a smaller contact area results when the femur is in contact with the convex portion.

Direct measurement of the collateral ligaments and indirect measurement of the cruciates was used by Wang [17] to determine the length patterns of these ligaments. The length pattern of a ligament is the manner in which the ligament changes length during flexion. It was found in this study that the collaterals did not markedly depart from behavior found in other studies. Additionally it was found that anterior-posterior movement of the femur on the tibia and rotation between the two would have little effect upon these ligaments. The length pattern for each collateral was very similar to the other indicating a symmetric performance.

The length patterns for the cruciate ligaments were found to be much more complex, mostly due to their geometrical location. A great deal of variation was observed and was generally attributed to "laxity" in the joint. Laxity was defined as the lack of a unique position of the femur on the tibia. Wang also observed that the length changes between the anterior and posterior cruciates were reciprocal, i.e., the anterior lengthening from extension to flexion and the posterior lengthening from flexion to extension. Internal rotation caused the anterior cruciate to lengthen when flexed beyond 30 degrees of flexion. This was not observed in the posterior cruciate. These phenomena were concluded to be functions of the placement of the ligament insertion and the center of rotation.

Wang and Walker [18] applied torques to amputated joints being held in about 25 degrees of flexion. These tests were done first with all of the ligamentous structures intact. As these ligaments were severed, torque and angular rotation data was gathered from this. They found:

(1) no obvious correlation with age, sex, or body build;

(2) that removal of the menisci increased laxity;

(3) the lateral ligaments were twice as important as the cruciates in controlling primary laxity.

Their most interesting finding was that increasing compressive axial load resulted in a marked reduction in laxity. The reason for this performance was not easily explained, but they could conclude that the source was not ligamentous because of the small amount of rotation. Their theory was that the menisci could be playing a more prominant role in load bearing performance than has been previously considered if it became tightly pressed between the tibial and femoral condyles. Then, frictional torque may have increased enough to appreciably absorb some of the rotatory torque. They conclude that the influence of axial load on the joint stability is greater than that of either the cruciates, collaterals or menisci.

Shaw and Murray [19] found that the main longitudinal rotatory motion of the knee was about the medial tibial spine. They also found that severing the anterior cruciate ligament would result in an anterior skid of the tibia on the femur in addition to the normal rotatory motion.

This survey of research studies illustrates the variety of work and the uncertainty of the role of some ligaments in knee joint stability.

Lubrication

Dowson [20] describes various lubrication regimes and their different behavior characteristics as an introduction to explain the lubrication mechanism in the knee. These mechanisms are:

(1) Hydrodynamic or self-acting lubrication, relative motion between the bearing surfaces generates the pressure in a bulk lubricant to support the load. No load can be supported when the surfaces are not moving.

(2) Hydrostatic or externally pressurized lubrication. The load supporting pressure in the lubricant is generated externally and independently of any surface motion.

(3) Boundary lubrication. This occurs when the bearing surfaces are separated by films of molecular proportions. In this condition frictional performance characteristics become dependent upon the chemical rather than physical properties of the lubricant.

(4) Elastohydrodynamic lubrication. This is a specialized case of hydrodynamic lubrication in which the lubricant pressures cause elastic deformation of the bearing surfaces. This, in return, influences the development of the pressure within the lubricant.

Initial study of the lubrication mechanism in human joints concentrated on hydrodynamic action. The low surface velocities were reconciled with the high viscosity synovial fluid to set up the necessary dynamic situation. Charnley [34] later proposed a boundary lubrication mechanism that in actuality looked like a hydrodynamic mechanism. Dowson attributes to McCutchen in 1959 the introduction of the so-called "weeping" lubrication, a condition in which the porous cartilage absorbed and exuded the synovial fluid in response to load.

Dowson [20] states that current thinking discards simple hydrodynamic lubrication because it neglects elastic effects. However boundary, weeping and elastohydrodynamic lubrication mechanisms are considered possible. He points out that weeping can be considered an extension of elastohydrodynamic lubrication, covering elastic porous bearing materials. Additionally the proposals of weeping or elastohydrodynamic mechanisms can include the possibility of local boundary lubrication effects with no loss of consistency.

Dowson concludes that the strongest evidence points to an elastohydrodynamic mechanism between porous surfaces with a boundary lubrication mechanism providing the surface protection in cases of severe load and little movement.

Injury Mechanisms

The five dominant soft tissue influences upon the stability of the knee are the anterior and posterior cruciate ligaments, the medial and lateral collateral ligaments and the menisci. When pathology (i.e., disease or injury) exists concerning one of these, a reduction in joint stability (the magnitude and nature varying between researchers) has been noted. The empirical observation concerning the circumstances around these injuries has been summarized by Smillie [21].

The medial collateral ligament is most commonly ruptured by a lateral blow to the joint in a situation where the knee is not allowed to flex. The restriction upon the flexing can either be a result of external influences, such as commonly occurs in contact sports, or internal as in the case of a hyperextended knee.

The next most frequently injured ligament is the anterior cruciate. There are four major mechanisms causing rupture of this ligament. When the medial collateral ligament has been torn then the anterior cruciate can be torn also by abduction of the tibia. Since forced abduction is the most common cause of medial collateral ruptures, anterior cruciate ruptures frequently occur with them due to the continued abduction of the tibia after the first rupture. The anterior cruciate can also be injured by a forced extension of the tibia in the absence of lateral rotation. This blocks the screw-home movement, which is the few degrees of lateral rotation at the end of extension which "locks" the joint in place. Direct injury, driving the femur backwards on a fixed tibia, and dislocation will also damage the anterior cruciate.

The posterior cruciate is injured by a force brought to bear against the flexed knee which strikes the anterior aspect of the tibial head and drives it backwards.

The lateral collateral ligament is injured by a sudden and powerful adduction of the tibia on the femur. This condition occurs in partial or complete dislocations.

This completes the background information for the understanding of the problem. The remaining sections of the thesis will describe the experimental work, the study of the data and the conclusions.

CHAPTER III

DESCRIPTION OF EXPERIMENTAL PROCEDURE

In order to study the geometrical interaction between the tibia and femur it is necessary to determine these surface geometries as precisely as possible. The following experimental procedure was used to accomplish this.

An intact knee joint from a young subject was obtained and major dissection was performed on it to remove all soft tissue. The articular surfaces were preserved in formalin. This hardens the tissue, coagulates the protein and permits the tissue to retain its cellular entities during sectioning, mounting and staining. Since formalin is a preservative the tissues can be kept in it for long periods of time [36]. Formalin fixation does not necessarily shrink the tissue but may, on occasion, swell them [33].

The determination of the surface geometry was to be accomplished by removing the surface at precise and uniform depths. The tissue removal was to be done on a vertical milling machine. In order to secure the bone in the vise of the milling machine it was necessary to mold the bond shaft vertically in a block of some hardening compound. To this end two plexiglass boxes were constructed to mount each bone in a molding compound. The top of the box was open and the sides and bottom were attached by screws as shown in Figure 4.

In the center of the bottom of the box was a small plexiglass rectangle. This rectangle, about 1 inch by 1/4 inch, was slightly tapered and oriented so that its sides were approximately parallel to those of the box. The function of the post was to allow slight movement of the joint when the shaft end of the bone was pressed down over it. This will tilt the bone but not allow it to rotate.

In each of the sides of the box was a screw that could be advanced through the box. These screws were made from 1/4 inch threaded rod with wing nuts silver soldered on one end. The other end of the rod was left blunt. These screws were mounted in the center of the sides of the box. The four screws would advance to converge on a point directly above the tapered post in the base of the box. The screws were essentially coplaner and hence when tightened upon the bone would exert negligible torque (moment).

The shaft ends of the tibia and femur were cut to about 8 centimeter length and two orthopaedic bone pins were inserted into the shafts perpendicular to each other. Each bone was pressed over the plexiglass rectangle in the bottom of each box whereupon the screws were tightened around the shaft and the molding compound (Appendix 4) poured around the base of the bone. The positioning of each bone, in the boxes, was that of the knee in about 10 degrees of flexion [32]. When the molding compound had hardened the sides and

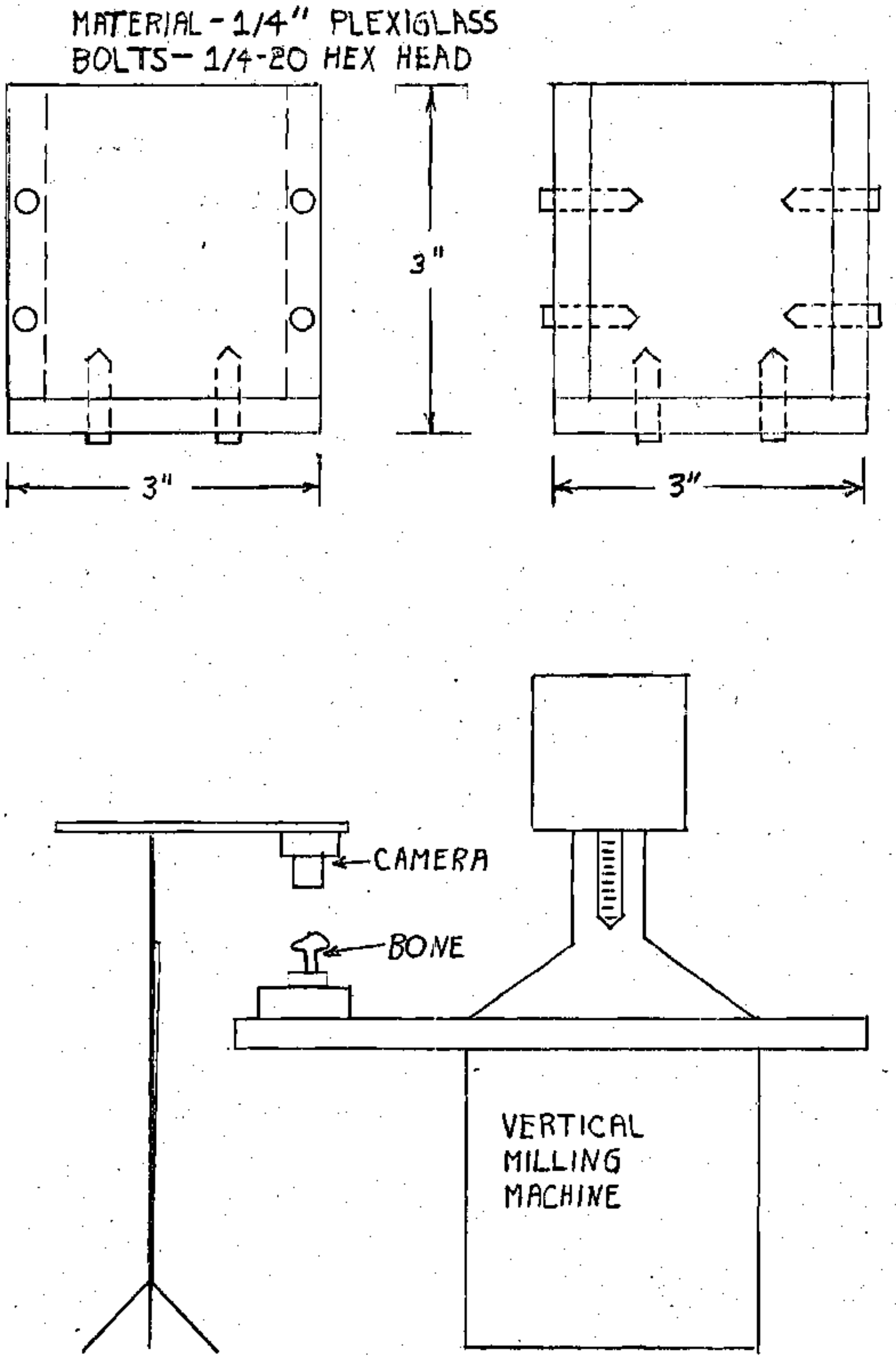


Figure 4. Mounting Box and Experimental Apparatus

bottom of the box were removed and the hardened block of resin with the firmly held bone was placed in the vise of the vertical milling machine, the bone being upright in order that the articular surface could be brought under the cutting tool, a 3/4 inch end mill. The initial position of the tool was selected as the point at which the tool first contacted the highest portion of the surface.

Then the surface was repeatedly cut with the tool each time removing a depth of 0.025 inch of the tibia and 0.050 inch of the femur. This cutting served to expose the portions of the articular surface that were at the same depth.

The table on the milling machine (Wells-Index) which held the vise and bone was capable of accurate lateral travel. As each cut was completed the table was moved to one side where the cut surface was brought under a 35 mm single lens reflex camera (Figure 4). This camera was mounted on a tripod stand above the mill. The cut surface was then photographed with slide film (tungsten balanced ektachrome). To enhance the clarity of these photographs the surface was highlighted with an inking roller.

The film was processed but not cut and mounted, thus assuring the proper picture sequence. The film was placed in a photographic enlarger where the images were projected onto a sheet of paper and the outlines of the cuts sketched. This formed a composite sketch of the different constant elevation lines. These contour maps, shown in Figures 5 and

6, are the tools by which the geometric influence upon the stability can be studied. However it is necessary to convert them to a usable numerical form.

CHAPTER IV

DATA ANALYSIS

Graphical Procedure

The graphical representation of the data produced the contour maps. This is excellent for visual purposes but is not conducive to more precise techniques of study. Because the contact between the surfaces was to be simulated on a digital computer it was necessary to perform a data reduction technique on the contour maps to create a more usable form of the data.

This was begun by placing the femoral and tibial surface contour maps over each other such that the two bone surfaces, described by the maps, were properly aligned over each other. The approximate center or rotation, that is the center of the axial rotation of the tibia around the femur, was also selected. By superimposing each contour map over the other it was placed on the lateral condyle spine posterior to the center [32].

Two congruent polar grids were constructed on each map centered at the axis of rotation (Figure 8). These grids consisted of a radial line every five degrees with ten circumferential lines for a total of 720 grid points. The radial distance between each circumferential line is constant.

At each of the 720 grid points an estimation of the articular cartilage surface height was made. This was done by a visual interpolative process between the map contours. In most cases a linear relationship was assumed between contour lines with the distances between the lines being visually estimated. This resulted in a mathematical representation of the tibial and femoral surfaces. The data reduction, being a visual interpolative process, has inherent errors in it. Since the surface of the articular cartilage is a smooth curve any description of it involving a series of straight lines is inaccurate. Even the contour maps themselves are subject to doubt due to limitations in the cutting characteristics of articular cartilage, the accuracy of the end milling process and photographic and visual resolution. However, reasonable precautions and care were taken to minimize these errors.

Numerical Simulation

Each data matrix then described each surface. To study the contact points of the two surfaces it was assigned that the contact would be at the reference points where the surfaces were the smallest distance apart. In the model this was done by subtracting each pair of elevation values and searching for the minimum.

To do this a computer program was written in Fortran language, that would read each of the data matrices and then search to find the "intersection" points of the two surfaces. The program simulates the placement of the two surfaces together where it rotates the tibia matrix and searches all the data points to find the points where the contact between the two surfaces would occur. A copy of the program and a more detailed description of it appear in Appendix 2.

CHAPTER V

OBSERVATIONS ON THE CONTOUR MAPS

Definition of Terms

Before entering into the actual discussion of the surfaces it is necessary to define some descriptive terms. "Proximal" will refer to a point that is closest to the main trunk or body while "distal" will refer to one that is further away. The "sagittal" plane is the plane that lies vertical from the front of the body to the rear. The "frontal" plane, also called the "coronal" plane, is also vertical but lies from the left to the right.

Proximal Tibial Surface

The knee studied was removed from a 19 year old female subject because of a bone tumor. Figure 5 shows the contour map of the tibia, approximately 3 times actual size. It is a right knee with the posterior, anterior, medial and lateral directions marked. The map is divided into the lateral and medial condyles. The intercondyler area between the tibial condyles contains soft tissue and serves as the attachments for the posterior and anterior cruciate ligaments and menisci. Since these areas are not articular or weight bearing surfaces, the contour lines in them have been omitted from the map in the interest of clarity. In the central

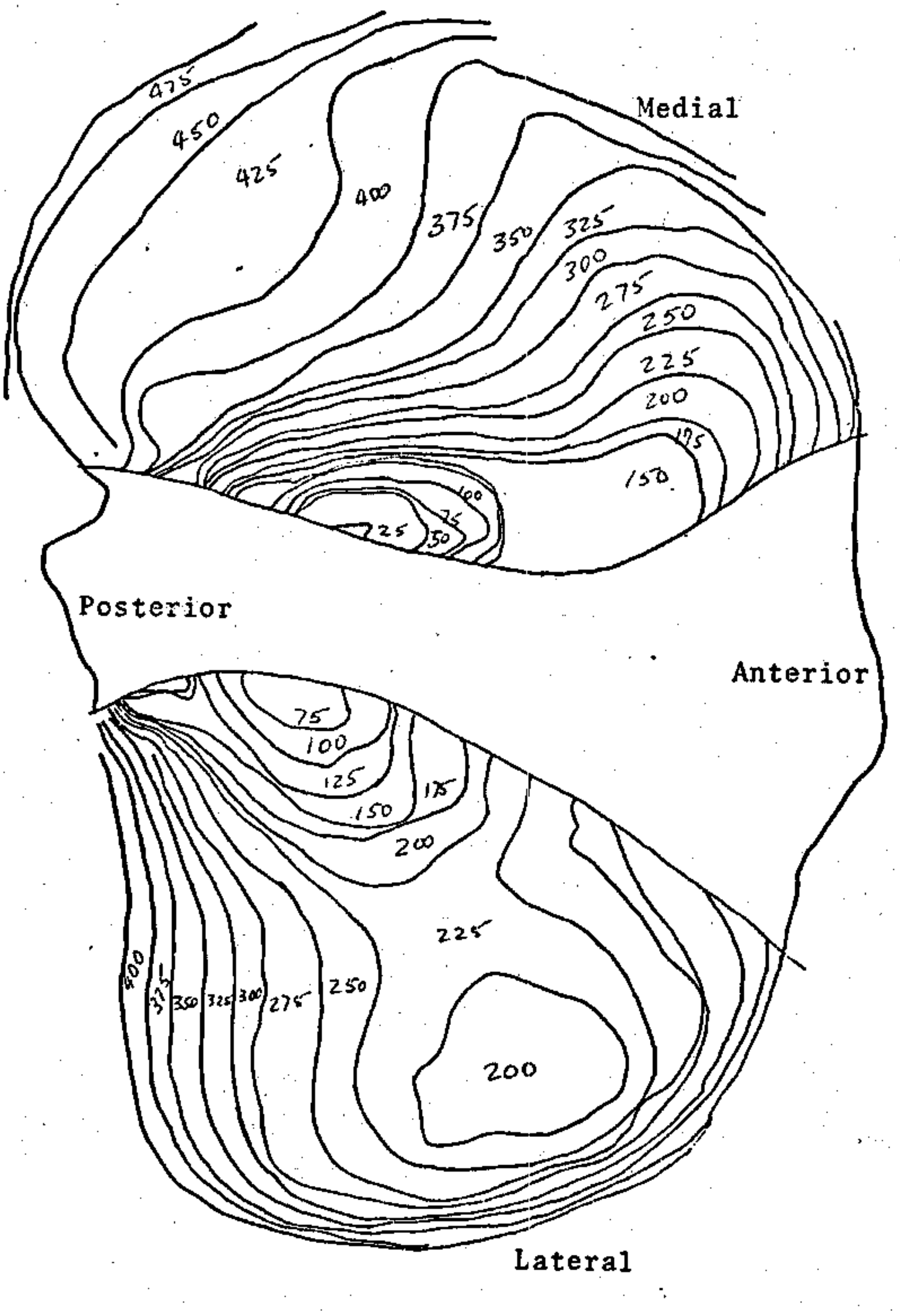


Figure 5. Tibial Contour Map

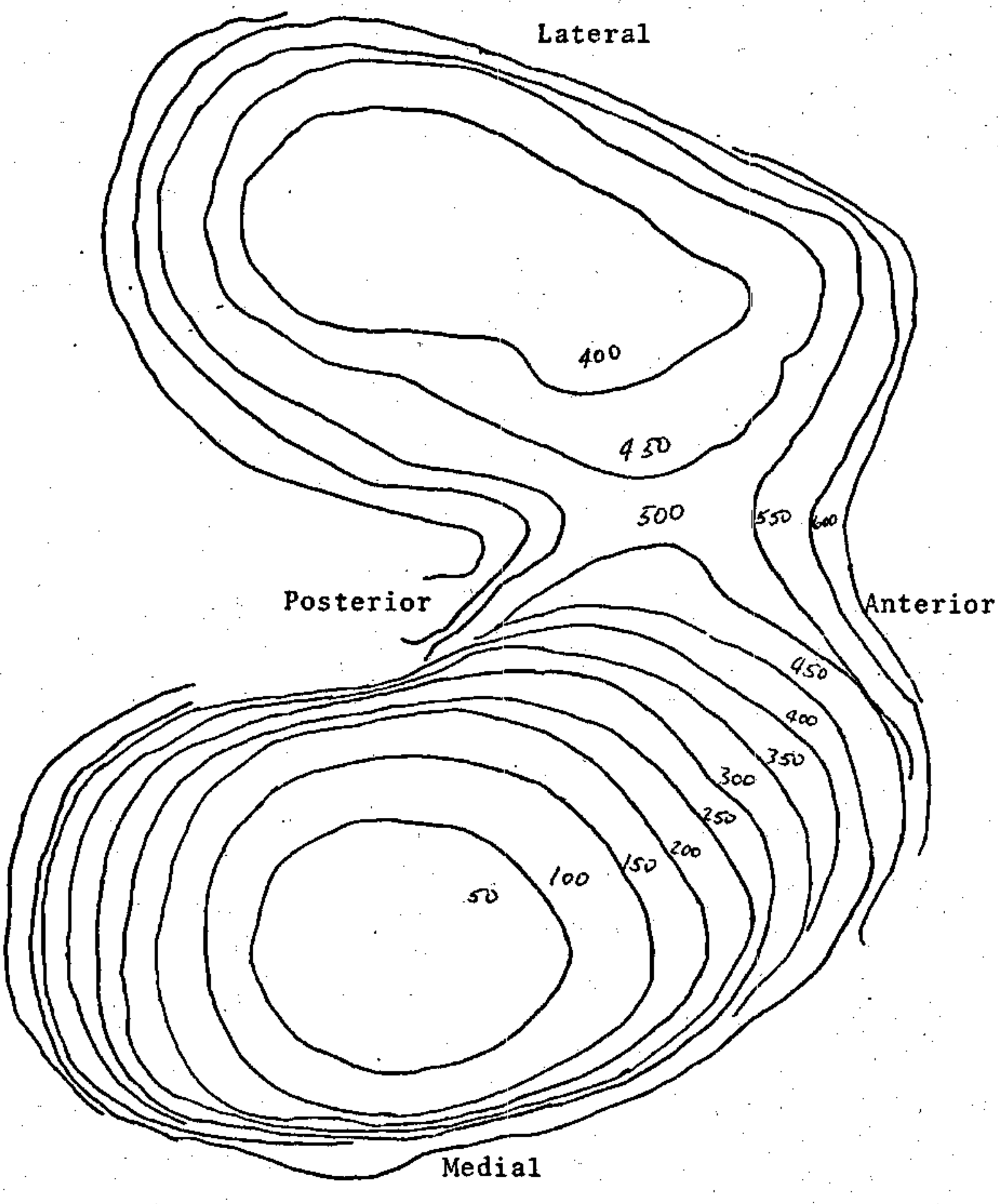


Figure 6. Femoral Contour Map

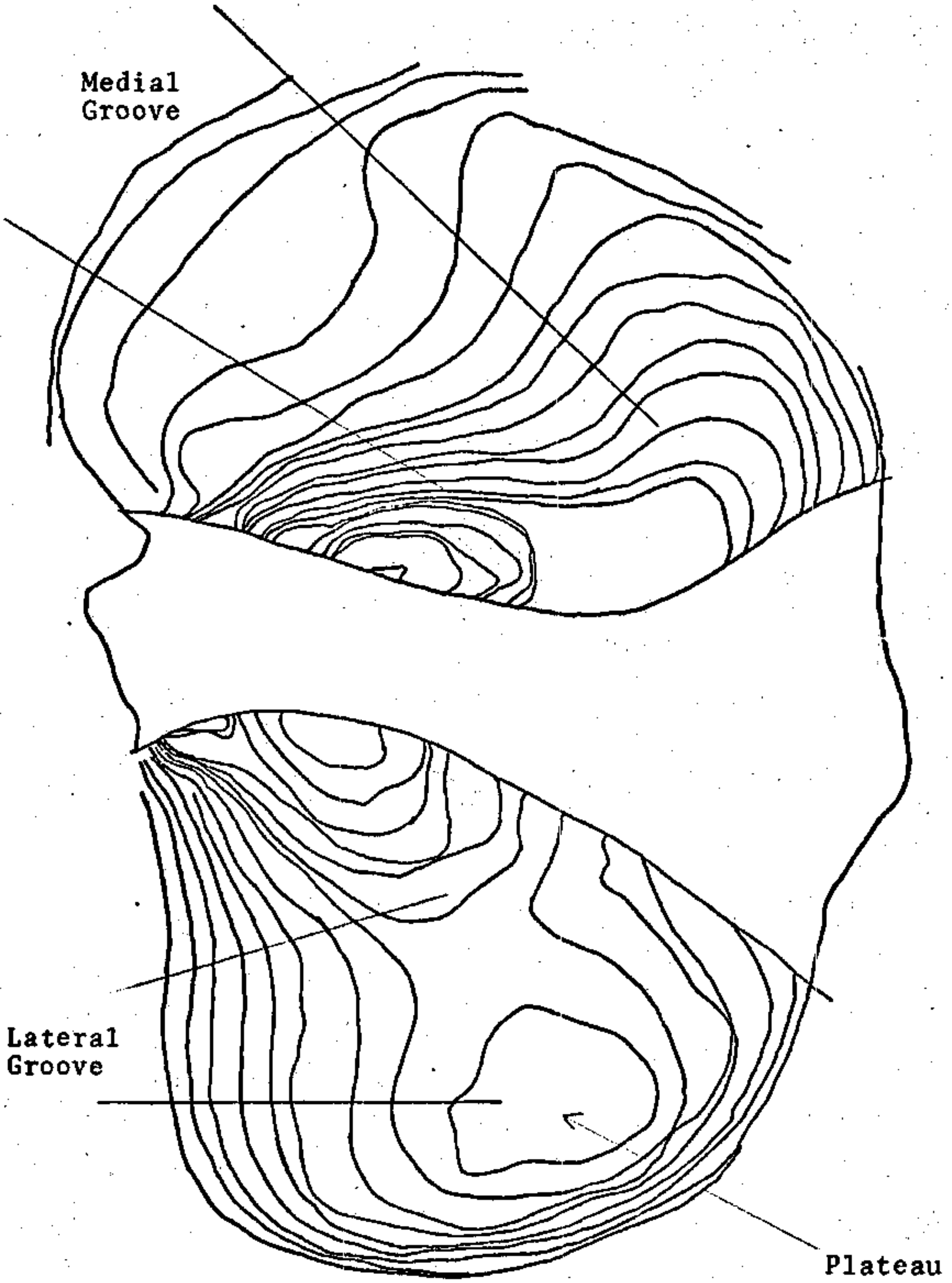


Figure 7. Tibial Contour Map

portion of the intercondylar area is the eminence or spine of the tibia. The elevation change represented by each contour line is 0.025 inch. The total tissue removed from the tibial surface was 0.475 inch. Therefore 19 separate cuts were made on the surface.

The medial condyle extended further posterior and anterior than did the lateral surface. It also had both the most distal and the most proximal points on the surface. On the anterior edge of the medial condyle the lowest elevation value recorded was 0.325 inch from the top. At the posterior edge the value was 0.475. Therefore the posterior edge of the medial condyle was 0.150 inch lower than the anterior. The 0.150 inch difference between the anterior and posterior edges was smoothly gained along the medial edge. Through the center of the condyle is a groove or an area of localized lower elevation. This groove forms a curve that first becomes noticeable at the 0.400 inch contour line, and then becomes less pronounced and narrower as it approaches the wide plateau at the 0.150 inch contour line. It lies roughly in the center of the condyle. Figure 7 is a copy of Figure 5 with these areas labeled. The shape of the plateau is rectangular yet with rounded corners and slightly curved sides. The long dimension of the plateau is in the sagittal plane. The lateral border of the plateau is the intercondylar area.

The contour lines, through which the groove passes before it reaches the plateau, become closer together nearer this plateau. This indicates that the elevation gradient, which is the change in elevation per unit distance traveled, is becoming steeper (i.e. has a relatively greater magnitude). This increase in elevation gradient along the groove is gradual in contrast to the area posterior to the groove, where there is an abrupt change in gradient at the 0.350 inch contour line. Also in contrast is the area anterior to the depression where the gradient is more nearly constant. The shape of the medial condyle is for the most part neither convex nor concave. It merely slopes downward from the higher areas near the anterior edge, to the posterior edge.

The lateral condyle has a more compact shape than does the medial. The anterior edge is slightly higher than the posterior; the last recorded value on the anterior edge being 0.350 inch and on the posterior, 0.400 inch. Although these changes are small they are not artifacts of cutting due to the care that was taken during the cutting procedure. Slightly anterior and lateral to the center of the condyle is an area where the contour line is closed. This indicates a plateau, an area higher than the surface around it. This plateau is contained within a 0.200 inch contour line. The area between the plateau and the 0.200 inch line on the spine is lower and hence forms a depression. From this depression to the posterior edge is a groove similar to the one on the medial condyle. It becomes less pronounced as it approaches the posterior edge. The elevation gradient through this groove remains nearly constant, until the 0.250 inch and the 0.275 inch contour lines, where the gradient nearly doubles. Medial to the groove the elevation gradients are much steeper whereas to the lateral side they are about the same. To the anterior of the depression between the spine and plateau the groove continues, but it is no longer ascending. It begins to descend and the articular surface terminates shortly. The higher elevations of the spine are more present in the lateral condyle than in the medial. As a result, the lateral condyle has shallower gradients in the lateral direction than the medial condyle has in the medial direction. The lateral edge of the lateral condyle has constant elevation gradients, smoothly approaching the lower points. The shape of the surface of the lateral condyle is then convex in the sagittal plane, through the observed depression. It is concave moving from the spine to the plateau. It is also slightly concave in the frontal plane through the depression posterior to the plateau.

Distal Femoral Surface

Figure 6 shows the contour map of the femoral articular surface. Each contour line represents an elevation difference of 0.050 inch. The total tissue removal was 0.700 inch for a total of 14 cuts. On the maps, the greatest depth labeled is 0.600 inch. This is due to the fact that the two successive contour lines were essentially the same for the 0.600 inch line. This indicated that the edges of the articular surface had become nearly vertical. The distal articular surface of the femur was divided into two completely convex condyles. The area between is convex in the sagittal plane and concave in the frontal plane. This area, especially to the anterior, is covered with articular cartilage. It contains soft tissue insertions for ligamentous structures, such as the cruciates.

The medial condyle is the larger condyle of the two. The most distal portion of the medial condyle is 0.400 inch higher in elevation than the most distal portion of the lateral. It also extends further in the posterior and anterior directions than does the lateral. The more distal contour lines are circular, but become oval proximally. The more proximal contours, before the sides of the condyle become vertical, form a distorted oval with the anterior segment of the oval bent toward the lateral side. The elevation gradients in the posterior and anterolateral direction are nearly constant and shallow. This means a slow elevation change with distance. On the medial and lateral side these gradients begin as shallow as those of the posterior and anterolateral, but become very steep within 0.150 inch. Distally the medial condyle is spherical and proximally like the shape of a wheel section.

The lateral condyle is similar in shape to the medial, but exhibits no distorted ovals. The elevation gradients are nearly constant and shallow on each side; except the lateral where they become steeper. The lateral condyle extends further proximal than the medial before the sides become too vertical to discern the contours.

The most distal point in the articular area between the condyles is between 0.450 inch and 0.500 inch, from the most distal point of the medial condyle. The cartilage in this area extends anteriorly nearly to the anterior edge of the condyles, but stops posteriorly a good distance from the posterior edge.

A point grid was constructed on the maps as described earlier and the data reduction performed to create the data matrices. A tabular listing of this data is included in Appendix 3.

This data was used in the search program to determine the contact points of the two surfaces. Table 1 lists the significant contact points yielded by the program. Figure 8 illustrates the tibia surface, the point grid and the contact points.

CHAPTER VI

DISCUSSION OF RESULTS

The contact points for the rotation of the femur on the tibia, listed in Table 1, are plotted in Figure 8. The total rotational change represented by these points is approximately 55 degrees. This much rotation would indicate an injury of the knee since in reality only a few degrees of rotation are normally possible. However these points serve a two fold purpose:

(1) To illustrate trends in normal rotational characteristics

(2) To explain the mechanism of injury during forced excessive rotation.

The contact occurs on the medial surfaces. This is to be expected since even though the medial tibial condyle is lower than the lateral tibial condyle, the medial femoral condyle is higher than the lateral femoral condyle by a greater amount. In reality there is surface contact on the lateral condyle. The model does not show it due to the quantification of the surface geometry.

The sequence in which the computer rotated the tibia matrix simulated internal rotation of the tibia in the knee model. During this simulated rotation the medial femoral

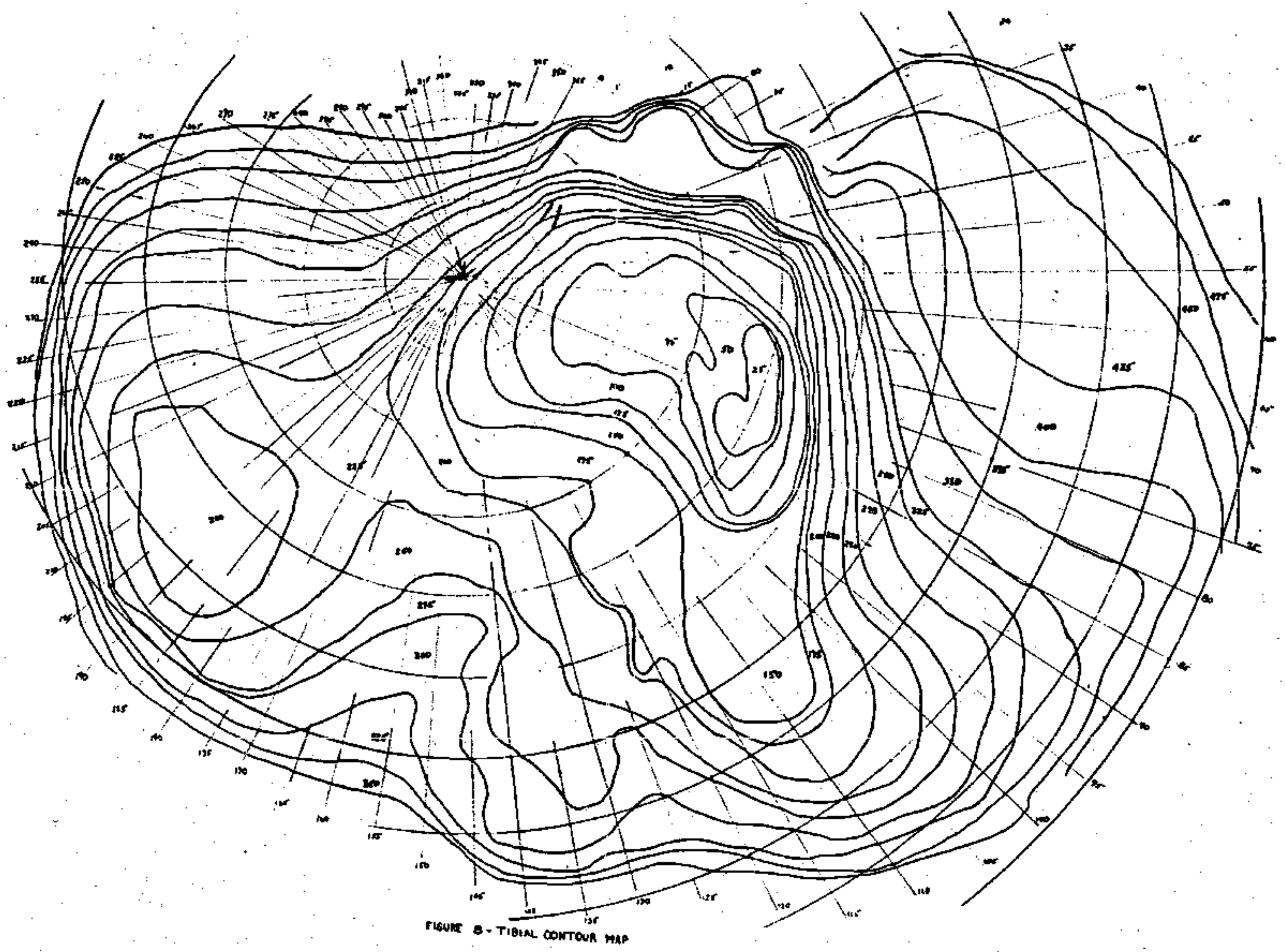


Figure 8. Tibial Contour Map with Coordinate Grid

Table 1. Contact Points

Degrees	Radial	Circumferential
-35	8	40
-30	8	40
-25	8	45
-20	8	45
-15	8	45
-10	8	55
-5	8	65
0	8	65
+5	8	65
+10	8	75
+15	7	75
[illegible]	8	75
	8	80
+20	8	80

condyle was moving along the groove in the medial tibial condyle towards the plateau in the anterior portion of the condyle. The tibial elevation increases along the path of this groove moving towards the plateau. The femoral condyle then was moving higher on the tibia surface. Even though the articular surfaces would remain in contact, the ligament insertion points would be pushed further apart by this movement. Alternately if the surfaces were not in contact initially then such motion would tend to bring them into contact. This would be more the situation in a clinical examination.

It is known that the lateral surfaces do contact and bear weight. This is due to the fact that in the young specimen that was modeled and also in five older tibias that were dissected previously, there was evidence of wear on the lateral condyle. In fact, on the older specimens the convex plateau was not evident. Its removal suggests some sort of response to load.

The lateral contact implies that as rotation proceeds the tibia must tilt somewhat to the lateral side due to the medial femoral condyle moving to higher elevations on the medial tibial condyle.

During external rotation the opposite takes place. The medial femoral surface would move to lower elevation points on the medial tibial condyle. The lateral femoral condyle moves towards the depression (or beyond) between the plateau and the spine. This tends to bring the ligament insertion points closer together thus reducing the stress in these ligaments. This increases the joint laxity.

This is of significance to a football player who injures the knee when hit on the lateral side of his leg while running and turning away from the direction of the hit. For example, if a player plants his right foot (which is not going to turn due to his cleats) and turns his body to the left to change direction of travel then his right knee is in forced external rotation. This means that the medial collateral ligament is loose, less able to sustain shock loading. Now if the player sustains a blow on the lateral side of his right leg then the leg abducts and the medial collateral ligament is shock loaded severely resulting in a rupture.

This result is not unique to football. Similar injurious situations occur in other sports, the circumstances being forced external rotation in near extension, with the possibility of a laterally applied force.

CHAPTER VII

CONCLUSIONS

On the basis of this study it is concluded that the surface geometry of the tibia and femur influence the rotatory stability of the knee joint. This is done by the movement of the ligament insertions during internal and external rotation. It can be seen that external rotation tends to reduce the tension in the collateral ligaments and internal tends to increase it.

No conclusions concerning the cruciates have been made due to their more complex function.

CHAPTER VIII

RECOMMENDATIONS

Several refinements can be offered to improve the convenience and accuracy of the method used in this work.

Concerning the choice of molding compound the epoxy resin was a very slow setting compound, requiring at least about 8 hours to cure. A faster compound, yet at the same time not liberating an excessive amount of heat, would be much more convenient. An acrylic compound, containing methylmethacrylate, perhaps will be more desirable.

Another important need is to increase resolution in the photographs. A larger format camera with a macro lens, use of a more specialized film, a more sophisticated lighting system and a more stable camera mounting system should yield better results. The orientation of the superimposed tibial and femoral maps is very important to duplicate the surface contact in the joint, a more precise method instead of a visual placement should be considered. This could be accomplished by attaching the two plexiglass boxes to a metal stand where one box would be exactly opposite the other. The two bones could then be cast in the molding compound before all the soft tissue were removed. Marks on the acrylic blocks could then be used to align the contour maps exactly.

A denser point grid on the maps will more accurately model the articular surface but this will necessitate a larger map and additional difficulty in reducing the data.

Grid density could be generated by a computer interpolation technique between the existing points. This could add more data points to the grid but the program would be very inefficient and difficult to run. Any gains in accuracy because of point density might be negated by inaccuracies in the interpolation itself.

APPENDICES

APPENDIX 1

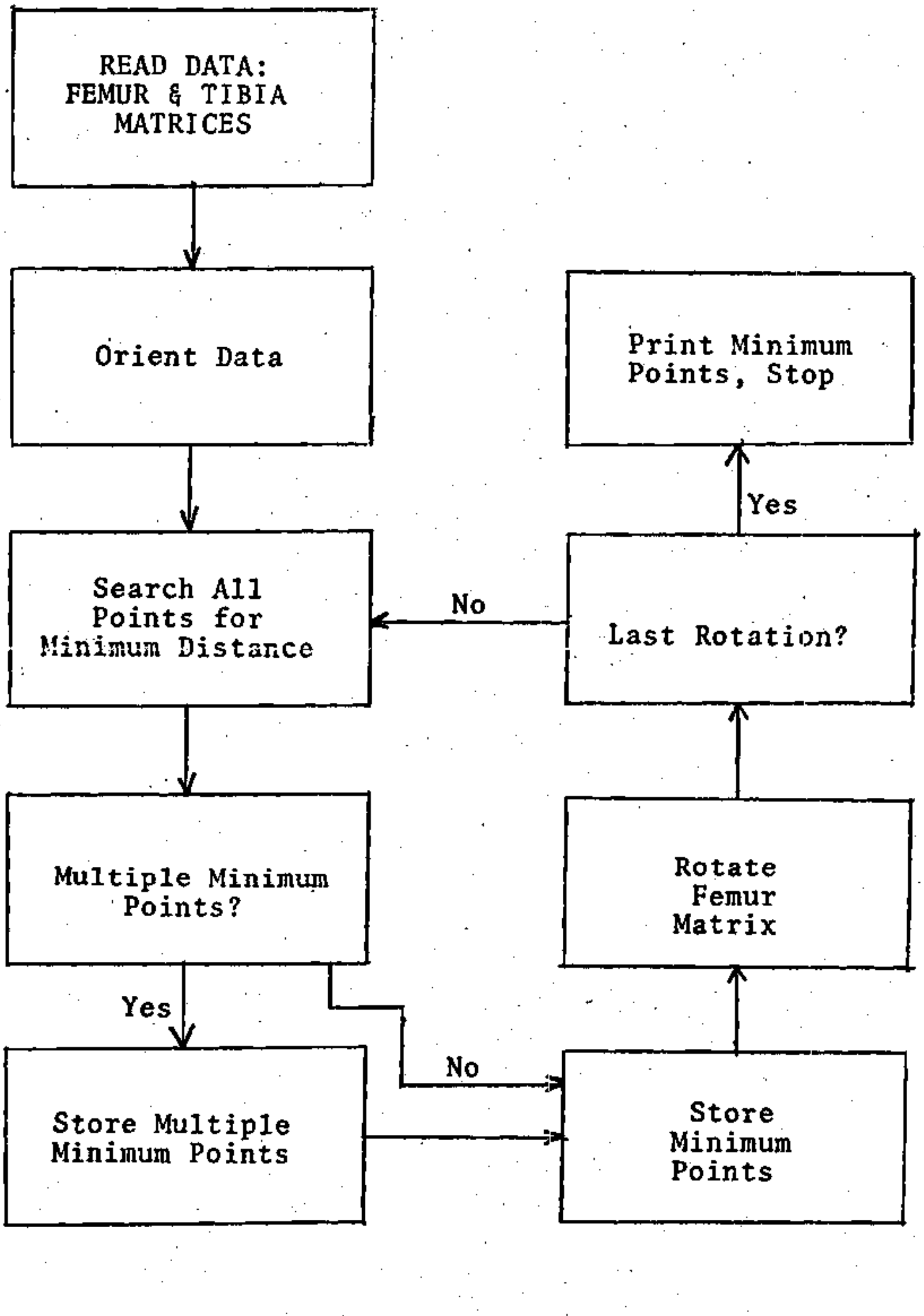
MOLDING COMPOUND INFORMATION

The molding compound used in the experimental procedure was #1039 epoxy resin mixed in appropriate amounts of #359 hardener. This is available from Magnolia Plastics, Peachtree Industrial Boulevard, Atlanta, Georgia.

APPENDIX 2

COMPUTER PROGRAM DESCRIPTION

Flow Chart


READ DATA:
FEMUR & TIBIA
MATRICES
Orient Data
Search All
Points for
Minimum Distance
Multiple Minimum
Points?
Yes
Store Multiple
Minimum Points
No
Store
Minimum
Points
Rotate
Femur
Matrix
Last Rotation?
No
Yes
Print Minimum
Points, Stop

Program Listing

```
      P 186
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION TZ(15,500),FZ(15,500),TEMP(15),AM(1000),RM(1000)
      INTEGER R,A,AMIN,RMIN,RM,AM
C FIRST WE READ THE TIBIA MATRIX
      READ(5,*) NPTS
      DO 18 I=1,NPTS
      READ(5,20) X,Y,Z
      R=X
      A=Y
18    TZ(R,A+5)=Z
20    FORMAT(F8.2,F12.2,F10.2)
C SECOND WE READ THE FEMUR MATRIX
      READ(5,*) NPTS
      DO 19 I=1,NPTS
      READ(5,20) X,Y,Z
      R=X
      A=Y
19    FZ(R,A+5)=Z
      WRITE(6,21)
21    FORMAT(  "    THE DATA HAS BEEN READ")
      DO 11 R=1,10
      DO 12 A=5,360,5
      TZ(R,A)=ABS(TZ(R,A)-475)+100
      FZ(R,A)=-FZ(R,A)+1000
12    CONTINUE
11    CONTINUE
      WRITE(6,22)
22    FORMAT(   "  NOW START THE SEARCH")
      N=0
499   A=5
      M=0
      OMIN=3000
      RMIN=0
      AMIN=0
500   R=1
510   O=TZ(R,A)-FZ(R,A)
      IF(O) 800,530,530
800   WRITE(6,900)
      STOP
```

```
530    IF(O-OMIN) 540,810,550
810    M=M+1
       RM(M)=R
       AM(M)=A
       GO TO 550
540    OMIN=O
       RMIN=R
       AMIN=A
       M=0
550    R=R+1
       IF(R-10) 510,560,820
820    WRITE(6,920) A,R
       STOP
560    A=A+5
       IF (A-365)  500,840,830
830    WRITE(6,930)
       STOP
840    WRITE(6,940)  N,RMIN,AMIN,OMIN
       IF(M) 951,951,948
948    WRITE(6,949)
949    FORMAT("  THE MULTIPLE MINIMUMS ARE")
       WRITE(6,950)((RM(I),AM(I)),I=1,M)
950    FORMAT(10(2X,2I5))
951    CONTINUE
       N=N+1
       IF(N-73)  570,580,580
570    DO 13 R=1,10
13    TEMP(R)=FZ(R,360)
       DO 14 R=1,10
       DO 15 J=10,360,5
      A=370-J
       FZ(R,A)=FZ(R,A-5)
15    CONTINUE
14    CONTINUE
       DO 17 R=1,10
17     FZ(R,5)=TEMP(R)
       GO TO 499
900    FORMAT("  O SOMEHOW WENT NEGATIVE")
910    FORMAT("   WE HAVE A PROBLEM HERE")
C STATEMENT 910 IMPLIES MULTIPLE MINIMUMS
920    FORMAT(2I10,  "WHAT HAPPENED TO R ")
C STATEMENT 920 IMPLIES THAT R EXCEEDED 10
930    FORMAT("  WHAT HAPPENED TO A")
C STATEMENT 930 IMPLIES THAT A EXCEEDED 360
940    FORMAT(" THE CONTACT FOR THE ",I3," ROTATION IS AT",2I3,F5.1)
580    STOP
       END
```

Program Description

In order for the listed program to be used the data must be placed in a data file, the tibia data preceding that of the femur. Each matrix is preceded by a data card containing the number of data points that are in the matrix.

The first five statements in the program are control and standard fortran declaration statements. Statements 5 through 20 in the search program stores the tibia and femur data in the computer in two 3 by 720 subscripted arrays. Statements 21 through 28 orient the two arrays. This is necessary due to the method in which the data was reduced. The orientation is accomplished by rotating the femur array 180 degrees and turning the tibia array "inside out." Statements 23 and 24 do this for the tibia and femur, respectively. Statements 29 through 65 are the actual search routine; Statement 36 being the center of interest. The quantity Q being calculated here is the difference in elevation values of the two points on the femur and tibia surface that have the same coordinates (angle and radius). The program seeks the minimum value from all 720 pairs of points and will print all points at which this value occurs.

Statements 66 through 75 rotate the tibia array elevation values 1 angle unit (5 degrees) and returns to search for a new minimum. The rotation is accomplished by an array swap method that merely moves the values for one angle unit to the same position at the next angle unit. This is done until the tibia has been completely rotated. These minimum distances are the points if the two surfaces were brought together, at which contact would occur.

Variable Dictionary

NPTS	number of data points, 720 in each array
x,y,z	Dummy variables
A	radial coordinate point
R	circumferential coordinate point
TZ	elevation coordinates of the tibia, function of A,R
FZ	elevation coordinates of the femur function of A,R
Q	distance between corresponding points on the tibia and femur surfaces
m	index variable
Q_{min}	minimum distance Q
A_{min}	radial coordinate point where minimum distance occurs
R_{min}	circumferential coordinate point where minimum distance occurs
AM	radial coordinate point where multiple minimums occur
RM	circumferential coordinate point where multiple minimums occur
temp	temporary storage array

APPENDIX 3

RAW DATA FROM CONTOUR MAP REDUCTION

Raw Data From Femur Map

①

Young Femur

R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z
1	0	510	3	20	700	5	40	275	7	60	20	9	80	80
2	0	610	4	20	700	6	40	175	8	60	20	10	80	250
3	0	700	5	20	700	7	40	170	9	60	50	1	85	485
4	0	700	6	20	700	8	40	190	10	60	250	2	85	565
5	0	700	7	20	700	9	40	245	1	65	510	3	85	600
6	0	700	8	20	700	10	40	450	2	65	700	4	85	330
7	0	700	9	20	700	1	45	520	3	65	700	5	85	130
8	0	700	10	20	700	2	45	700	4	65	700	6	85	112
9	0	700	1	25	515	3	45	700	5	65	115	7	85	55
10	0	700	2	25	700	4	45	700	6	65	50	8	85	75
1	5	515	3	25	700	5	45	210	7	65	18	9	85	110
2	5	615	4	25	700	6	45	125	8	65	12	10	85	300
3	5	700	5	25	700	7	45	110	9	65	45	1	90	482
4	5	700	6	25	500	8	45	120	10	65	225	2	90	560
5	5	700	7	25	500	9	45	162	1	70	505	3	90	700
6	5	700	8	25	700	10	45	260	2	70	700	4	90	[illegible]
7	5	700	9	25	700	1	50	520	3	70	700	5	90	225
8	5	700	10	25	700	2	50	700	4	70	700	6	90	150
9	5	700	1	30	525	3	50	700	5	70	120	7	90	130
10	5	700	2	30	700	4	50	700	6	70	55	8	90	130
1	10	520	3	30	700	5	50	150	7	70	22	9	90	155
2	10	620	4	30	700	6	50	87	8	70	18	10	90	275
3	10	700	5	30	700	7	50	62	9	70	45	1	95	480
4	10	700	6	30	335	8	50	70	10	70	250	2	95	545
5	10	700	7	30	325	9	50	120	1	75	500	3	95	600
6	10	700	8	30	420	10	50	255	2	75	600	4	95	425
7	10	700	9	30	700	1	55	515	3	75	700	5	95	250
8	10	700	10	30	700	2	55	700	4	75	500	6	95	200
9	10	700	1	35	525	3	55	700	5	75	125	7	95	180
10	10	700	2	35	700	4	55	700	6	75	70	8	95	182
1	15	525	3	35	700	5	55	125	7	75	37	9	95	275
2	15	625	4	35	700	6	55	60	8	75	30	10	95	400
3	15	700	5	35	350	7	55	35	9	75	65	1	100	480
4	15	700	6	35	240	8	55	32	10	75	250	2	100	520
5	15	700	7	35	290	9	55	75	1	80	490	3	100	580
6	15	700	8	35	325	10	55	250	2	80	580	4	100	495
7	15	200	9	35	350	1	60	515	3	80	600	5	100	312
8	15	700	10	35	700	2	60	700	4	80	350	6	100	250
9	15	700	1	40	525	3	60	700	5	80	100	7	100	250
10	15	700	2	40	700	4	60	700	6	80	50	8	100	250
1	20	525	3	40	700	5	60	120	7	80	62	9	100	300
2	20	700	4	40	700	6	60	45	8	80	50	10	100	460

(2)

Femur

Young

R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z
1	105	475	3	125	450	5	145	425	7	165	700	9	185	700
2	105	495	4	125	460	6	145	440	8	165	700	10	185	700
3	105	560	5	125	500	7	145	600	9	165	700	1	190	[illegible]
4	105	455	6	125	520	8	145	700	10	165	700	2	190	360
5	105	370	7	125	600	9	145	700	1	170	400	3	190	390
6	105	312	8	125	700	10	145	700	2	170	380	4	190	425
7	105	[illegible]	9	125	700	1	150	475	3	170	365	5	190	[illegible]
8	105	312	10	125	700	2	150	410	4	170	310	6	190	700
9	105	[illegible]	1	130	450	3	150	390	5	170	425	7	190	700
10	105	550	2	130	440	4	150	345	6	170	520	8	190	700
1	110	[illegible]	3	130	430	5	150	415	7	170	700	9	190	700
2	110	450	4	130	440	6	150	465	8	170	700	10	190	700
3	110	500	5	130	465	7	150	550	9	170	700	1	195	390
4	110	520	6	130	530	8	150	700	10	175	700	2	195	350
5	110	415	7	130	700	9	150	700	1	175	395	3	195	390
6	110	390	8	130	700	10	150	700	2	175	375	4	195	435
7	110	260	9	130	700	1	155	420	3	175	375	5	195	700
8	110	380	10	130	700	2	155	400	4	175	395	6	195	700
9	110	437	1	135	445	3	155	[illegible]	5	175	[illegible]	7	195	700
10	110	600	2	135	430	4	155	385	6	175	[illegible]	8	195	700
1	115	465	3	135	420	5	155	315	7	175	700	9	195	700
2	115	475	4	135	425	6	155	445	8	175	700	10	195	700
3	115	500	5	135	455	7	155	545	9	175	700	1	200	390
4	115	465	6	135	525	8	155	700	10	175	700	2	200	350
5	115	430	7	135	700	9	155	700	1	180	395	3	200	390
6	115	430	8	135	700	10	155	700	2	180	365	4	200	440
7	115	425	9	135	700	1	160	415	3	180	375	5	200	700
8	115	445	10	135	700	2	160	395	4	180	400	6	200	700
9	115	550	1	140	440	3	160	375	5	180	475	7	200	700
10	115	700	2	140	420	4	160	355	6	180	700	8	200	700
1	120	460	3	140	400	5	160	395	7	180	700	9	200	700
2	120	462	4	140	420	6	160	440	8	180	700	10	200	700
3	120	475	5	140	440	7	160	550	9	180	700	1	205	700
4	120	500	6	140	515	8	160	700	10	180	700	2	205	385
5	120	460	7	140	700	9	160	700	1	185	345	3	205	350
6	120	475	8	140	700	10	160	700	2	185	365	4	205	[illegible]
7	120	525	9	140	700	1	165	405	3	185	380	5	205	440
8	120	600	10	140	700	2	165	390	4	185	415	6	205	700
9	120	700	1	145	425	3	165	365	5	185	[illegible]	7	205	700
10	120	700	2	145	415	4	165	385	6	185	700	8	205	700
1	125	455	3	145	395	5	165	410	7	185	700	9	205	700
2	125	450	4	145	405	6	165	460	8	185	700	10	205	700

3

R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z
1	210	380	3	230	395	5	250	700	7	270	700	9	290	700
2	210	350	4	230	500	6	250	700	8	270	700	10	290	700
3	210	370	5	230	700	7	250	700	9	270	700	1	295	430
4	210	[illegible]	6	230	700	8	250	700	10	270	700	2	295	460
5	210	700	7	230	700	9	250	700	1	275	395	3	295	535
6	210	700	8	230	700	10	250	700	2	275	398	4	295	700
7	210	700	9	230	700	1	255	392	3	275	465	5	295	700
8	210	700	10	230	700	2	255	355	4	275	570	6	295	700
9	210	700	1	235	380	3	255	415	5	275	700	7	295	700
10	210	700	2	235	370	4	255	505	6	275	700	8	295	700
1	215	380	3	235	395	5	255	700	7	275	700	9	295	700
2	215	360	4	235	490	6	255	700	8	275	700	10	295	700
3	215	390	5	235	700	7	255	700	9	275	700	1	300	445
4	215	445	6	235	700	8	255	700	10	275	700	2	300	475
5	215	700	7	235	700	9	255	700	1	280	400	3	300	555
6	215	700	8	235	700	10	255	700	2	280	415	4	300	700
7	215	700	9	235	700	1	260	395	3	280	430	5	300	700
8	215	700	10	235	700	2	260	390	4	280	585	6	300	700
9	215	700	1	240	390	3	260	425	5	280	700	7	300	700
10	215	700	2	240	375	4	260	520	6	280	700	8	300	700
1	220	380	3	240	395	5	260	700	7	280	700	9	300	700
2	220	360	4	240	490	6	260	700	8	280	700	10	300	700
3	220	390	5	240	700	7	260	700	9	280	700	1	305	450
4	220	465	6	240	700	8	260	700	10	280	700	2	305	480
5	220	700	7	240	700	9	260	700	1	285	410	3	305	575
6	220	700	8	240	700	10	260	700	2	285	430	4	305	700
7	220	700	9	240	700	1	265	395	3	285	440	5	305	700
8	220	700	10	240	700	2	265	395	4	285	700	6	305	700
9	220	700	1	245	390	3	265	435	5	285	700	7	305	700
10	220	700	2	245	385	4	265	530	6	285	700	8	305	700
1	225	380	3	245	398	5	265	700	7	285	700	9	305	700
2	225	365	4	245	440	6	265	700	8	285	700	10	305	700
3	225	390	5	245	700	7	265	700	9	285	700	1	310	455
4	225	440	6	245	700	8	265	700	10	285	700	2	310	495
5	225	700	7	245	700	9	265	700	1	290	420	3	310	590
6	225	700	8	245	700	10	265	700	2	290	450	4	310	700
7	225	700	9	245	700	1	270	395	3	290	510	5	310	700
8	225	700	10	245	700	2	270	395	4	290	700	6	310	700
9	225	700	1	250	390	3	270	450	5	290	700	7	310	700
10	225	700	2	250	380	4	270	550	6	290	700	8	310	700
1	230	380	3	250	400	5	270	700	7	290	700	9	310	700
2	230	370	4	250	500	6	270	700	8	290	700	10	310	700

④

Young Kumar

R	θ	Z	R	θ	Z	R	θ	Z	X	Y	Z	X	Y	Z
1	315	460	3	335	700	5	355	700						
2	315	515	4	335	700	6	355	700						
3	315	610	5	335	700	7	355	700						
4	315	700	6	335	700	8	355	700						
5	315	700	7	335	700	9	355	700						
6	315	700	8	335	700	10	355	700						
7	315	700	9	335	700									
8	315	700	10	335	700									
9	315	700	1	340	485									
10	315	700	2	340	580									
1	320	470	3	340	700									
2	320	535	4	340	700									
3	320	700	5	340	700									
4	320	700	6	340	700									
5	320	700	7	340	700									
6	320	700	8	340	700									
7	320	700	9	340	700									
8	320	700	10	340	700									
9	320	700	1	345	490									
10	320	700	2	345	590									
1	325	475	3	345	700									
2	325	550	4	345	700									
3	325	700	5	345	700									
4	325	700	6	345	700									
5	325	700	7	345	700									
6	325	700	8	345	700									
7	325	700	9	345	700									
8	325	700	10	345	700									
9	325	700	1	350	500									
10	325	700	2	350	600									
1	330	465	3	350	700									
2	330	560	4	350	700									
3	330	700	5	350	700									
4	330	700	6	350	700									
5	330	700	7	350	700									
6	330	700	8	350	700									
7	330	700	9	350	700									
8	330	700	10	350	700									
9	330	700	1	355	505									
10	330	700	2	355	610									
1	335	480	3	355	700									
2	335	575	4	355	700									

Raw Data From Tibia Map

① Young TIBIA

R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z	R	θ	Z
1	0	245	3	20	280	5	40	400	7	60	405	9	80	350
2	0	315	4	20	360	6	40	412	8	60	420	10	80	400
3	0	475	5	20	475	7	40	430	9	60	425	1	85	90
4	0	475	6	20	475	8	40	470	10	60	475	2	85	70
5	0	475	7	20	475	9	40	475	1	65	90	3	85	80
6	0	475	8	20	475	10	40	475	2	65	65	4	85	5
7	0	475	9	20	475	1	45	125	3	65	45	5	[illegible]	175
8	0	475	10	20	475	2	45	90	4	65	75	6	85	[illegible]
9	0	475	1	25	132	3	45	120	5	65	295	7	85	313
10	0	475	2	25	145	4	45	275	6	65	375	8	85	325
1	5	230	3	25	285	5	45	[illegible]	7	65	395	9	85	337
2	5	290	4	25	[illegible]	6	45	400	8	65	400	10	85	425
3	5	475	5	25	475	7	45	420	9	65	400	1	70	90
4	5	475	6	25	475	8	45	400	10	65	475	2	70	75
5	5	475	7	25	475	9	45	475	1	70	90	3	70	87
6	5	475	8	25	475	10	45	475	2	70	65	4	70	25
7	5	475	9	25	475	1	50	112	3	70	55	5	70	137
8	5	475	10	25	475	2	50	97	4	70	20	6	70	255
9	5	475	1	30	133	3	50	95	5	70	260	7	90	200
10	5	475	2	30	175	4	50	185	6	70	350	8	90	[illegible]
1	10	290	3	30	285	5	50	355	7	70	385	9	90	320
2	10	280	4	30	350	6	50	390	8	70	387	10	90	475
3	10	375	5	30	450	7	50	412	9	70	385	1	95	90
4	10	475	6	30	450	8	50	435	10	70	425	2	95	85
5	10	475	7	30	475	9	50	460	1	75	90	3	95	105
6	10	475	8	30	475	10	50	425	2	75	65	4	95	75
7	10	475	9	30	475	1	55	105	3	75	50	5	95	135
8	10	475	10	30	475	2	55	75	4	75	5	6	95	215
9	10	475	1	35	190	3	[illegible]	72	5	75	225	7	95	240
10	10	475	2	35	135	4	55	120	6	75	337	8	95	260
1	15	200	3	35	275	5	55	337	7	75	365	9	95	[illegible]
2	15	337	4	35	300	6	55	[illegible]	8	75	370	10	95	475
3	15	295	5	35	437	7	55	410	9	75	370	1	100	95
4	15	475	6	35	430	8	55	420	10	75	400	2	100	87
5	15	475	7	35	445	9	55	440	1	80	90	3	100	135
6	15	475	8	35	475	10	55	475	2	80	65	4	100	115
7	15	475	9	35	475	1	60	100	3	80	55	5	100	130
8	15	475	10	35	475	2	60	65	4	80	5	6	100	175
9	15	475	1	40	[illegible]	3	60	50	5	80	200	7	100	205
10	15	475	2	40	110	4	60	110	6	80	315	8	100	235
1	20	175	3	40	200	5	60	300	7	80	395	9	100	290
2	20	230	4	40	285	6	60	385	8	80	350	10	100	475

(2)

Young

R	θ	z	R	θ	z	R	θ	z	R	θ	z	R	θ	z
1	105	100	3	125	187	5	145	290	7	165	475	9	185	475
2	105	95	4	175	200	6	145	295	8	165	475	10	[illegible]	475
3	105	150	5	125	210	7	145	300	9	165	475	1	190	200
4	105	150	6	125	250	8	145	475	10	165	475	2	190	215
5	105	135	7	125	280	9	145	475	1	170	180	3	190	210
6	105	140	8	125	475	10	145	475	2	170	200	4	190	180
7	105	170	9	125	475	1	150	145	3	170	220	5	190	190
8	105	215	10	175	475	2	150	180	4	170	225	6	190	275
9	105	300	1	130	125	3	150	220	5	170	200	7	190	475
10	105	475	2	130	155	4	150	265	6	170	287	8	190	475
1	110	105	3	130	200	5	150	290	7	170	475	9	190	475
2	110	100	4	130	210	6	150	295	8	170	475	10	190	475
3	110	165	5	130	220	7	150	475	9	170	475	1	195	212
4	110	160	6	130	235	8	150	475	10	170	475	2	195	220
5	110	140	7	130	270	9	150	475	1	175	185	3	195	210
6	110	145	8	130	475	10	150	475	2	175	205	4	195	185
7	110	165	9	130	475	1	155	180	3	175	215	5	195	195
8	110	225	10	130	475	2	155	188	4	175	215	6	195	287
9	110	325	1	135	130	3	155	225	5	175	255	7	195	475
10	110	475	2	135	155	4	155	260	6	175	275	8	195	475
1	115	110	3	135	210	5	155	290	7	175	475	9	195	475
2	115	135	4	135	220	6	155	320	8	175	475	10	195	475
3	115	175	5	135	235	7	155	475	9	175	475	1	200	225
4	115	162	6	135	240	8	155	475	10	175	475	2	200	225
5	115	160	7	135	262	9	155	475	1	180	190	3	200	210
6	115	150	8	135	475	10	155	475	2	180	205	4	200	185
7	115	200	9	135	475	1	160	170	3	180	210	5	200	200
8	115	295	10	135	475	2	160	195	4	180	205	6	200	325
9	115	475	1	140	135	3	160	225	5	180	210	7	200	475
10	115	475	2	140	155	4	160	295	6	180	250	8	200	475
1	120	112	3	140	213	5	160	285	7	180	475	9	200	475
2	120	140	4	140	250	6	160	315	8	180	475	10	200	475
3	120	185	5	140	245	7	160	475	9	180	475	1	205	230
4	120	170	6	140	250	8	160	475	10	180	475	2	205	235
5	120	170	7	140	295	9	160	475	1	185	195	3	205	215
6	120	210	8	140	475	10	160	475	2	185	210	4	205	190
7	120	250	9	140	475	1	165	175	3	185	210	5	205	215
8	120	315	10	140	475	2	165	200	4	185	195	6	205	360
9	120	475	1	145	140	3	165	225	5	185	195	7	205	475
10	120	475	2	145	165	4	165	235	6	185	265	8	205	475
1	125	120	3	145	215	5	165	265	7	185	475	9	205	475
2	125	150	4	145	262	6	165	300	8	185	475	10	205	475

(3)

young

R	θ	z	R	θ	z	R	θ	z	R	θ	z	R	θ	z
1	210	235	3	230	255	5	250	475	7	270	475	9	290	475
2	210	240	4	230	250	6	250	475	8	270	475	10	290	475
3	210	220	5	230	340	7	250	475	9	270	475	1	295	310
4	210	195	6	230	475	8	250	475	10	270	475	2	295	390
5	210	225	7	230	475	9	250	475	1	275	280	3	295	475
6	210	475	8	230	475	10	250	475	2	275	350	4	295	475
7	210	475	9	230	475	1	255	275	3	275	400	5	295	475
8	210	475	10	230	475	2	255	310	4	275	475	6	295	475
9	210	475	1	235	260	3	255	325	5	275	475	7	295	475
10	210	475	2	235	270	4	255	355	6	275	475	8	295	475
1	215	240	3	235	262	5	255	475	7	275	475	9	295	475
2	215	295	4	255	262	6	255	475	8	275	475	10	295	475
3	215	225	5	235	365	7	255	475	9	275	475	1	300	310
4	215	210	6	235	475	8	255	475	10	275	475	2	300	400
5	215	290	7	235	475	9	255	475	1	280	300	3	300	475
6	215	475	8	235	475	10	255	475	2	280	265	4	300	475
7	215	475	9	235	475	1	260	280	3	280	475	5	300	475
8	215	475	10	235	475	2	260	320	4	280	475	6	300	475
9	215	475	1	240	265	3	260	390	5	280	475	7	300	475
10	215	475	2	240	275	4	260	387	6	280	475	8	300	475
1	220	295	3	240	270	5	265	475	7	280	475	9	300	475
2	220	250	4	240	275	6	260	475	8	280	475	10	300	475
3	220	255	5	240	400	7	260	475	9	280	475	1	305	310
4	220	295	6	240	475	8	260	475	10	280	475	2	305	475
5	220	265	7	240	475	9	260	475	1	285	300	3	305	475
6	220	475	8	240	475	10	260	475	2	285	375	4	305	475
7	220	475	9	240	475	1	265	285	3	285	475	5	305	475
8	220	475	10	240	475	2	265	330	4	285	475	6	305	475
9	220	475	1	245	265	3	265	360	5	285	475	7	305	475
10	220	475	2	245	287	4	265	475	6	285	475	8	305	475
1	225	250	3	245	287	5	265	475	7	285	475	9	305	475
2	225	260	4	245	312	6	265	475	8	285	475	10	305	475
3	225	270	5	245	475	7	265	475	9	285	475	1	310	310
4	225	237	6	245	475	8	265	475	10	285	475	2	310	475
5	225	300	7	245	475	9	265	475	1	290	305	3	310	475
6	225	475	8	245	475	10	265	475	2	290	387	4	310	475
7	225	475	9	245	475	1	270	290	3	290	475	5	310	475
8	225	475	10	245	475	2	270	340	4	290	475	6	310	475
9	225	475	1	250	270	3	270	275	5	290	475	7	310	475
10	225	475	2	250	300	4	270	475	6	290	475	8	310	475
1	230	255	3	250	310	5	270	475	7	290	475	9	310	475
2	230	265	4	250	335	6	270	475	8	290	475	10	310	475

R	θ	Z	R	θ	Z	R	θ	Z	X	Y	Z	X	Y	Z
1	315	305	3	335	475	5	355	475						
2	315	475	4	335	475	6	355	475						
3	315	475	5	335	475	7	355	475						
4	315	475	6	335	475	8	355	475						
5	315	475	7	335	475	9	355	475						
6	315	475	8	335	475	10	355	475						
7	315	475	9	335	475									
8	315	475	10	335	475									
9	315	475	1	340	280									
10	315	475	2	340	475									
1	320	300	3	340	475									
2	320	475	4	340	475									
3	320	475	5	340	475									
4	320	475	6	340	475									
5	320	475	7	340	475									
6	320	475	8	340	475									
7	320	475	9	340	475									
8	320	475	10	340	475									
9	320	475	1	345	275									
10	320	475	2	345	475									
1	325	295	3	345	475									
2	325	475	4	345	475									
3	325	475	5	345	475									
4	325	475	6	345	475									
5	325	475	7	345	475									
6	325	475	8	345	475									
7	325	475	9	345	475									
8	325	475	10	345	475									
9	325	475	1	350	265									
10	325	475	2	350	475									
1	330	290	3	350	475									
2	330	475	4	350	475									
3	330	475	5	350	475									
4	330	475	6	350	475									
5	330	475	7	350	475									
6	330	475	8	350	475									
7	330	475	9	350	475									
8	330	475	10	350	475									
9	330	475	1	355	255									
10	330	475	2	355	475									
1	335	285	3	355	475									
2	335	475	4	355	475									

APPENDIX 4

COMPUTER OUTPUT

Computer Output
Femoral Coordinates

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THE CONTACT FOR THE   0 ROTATION IS AT  8 65 76.0
THE CONTACT FOR THE   1 ROTATION IS AT  8 70 68.0
THE CONTACT FOR THE   2 ROTATION IS AT  8 65 61.0
THE CONTACT FOR THE   3 ROTATION IS AT  8 60 43.0
THE CONTACT FOR THE   4 ROTATION IS AT  8 65 26.0
THE CONTACT FOR THE   5 ROTATION IS AT  8 70 18.0
THE CONTACT FOR THE   6 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE   7 ROTATION IS AT  8 75 19.0
THE CONTACT FOR THE   8 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE   9 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  10 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  11 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  12 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  13 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  14 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  15 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  16 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  17 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  18 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  19 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  20 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  21 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  22 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  23 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  24 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  25 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  26 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  27 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  28 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  29 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  30 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  31 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  32 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  33 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  34 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  35 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  36 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  37 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  38 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  39 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  40 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  41 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  42 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  43 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  44 ROTATION IS AT  8 70 13.0
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THE CONTACT FOR THE  45 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  46 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  47 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  48 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  49 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  50 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  51 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  52 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  53 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  54 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  55 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  56 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  57 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  58 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  59 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  60 ROTATION IS AT  8 70 13.0
THE CONTACT FOR THE  61 ROTATION IS AT  8 75 19.0
THE CONTACT FOR THE  62 ROTATION IS AT  8 80 31.0
THE CONTACT FOR THE  63 ROTATION IS AT  9 75 46.0
THE CONTACT FOR THE  64 ROTATION IS AT  9 80 66.0
THE CONTACT FOR THE  65 ROTATION IS AT  9 85 81.0
THE CONTACT FOR THE  66 ROTATION IS AT  9 90111.0
THE CONTACT FOR THE  67 ROTATION IS AT  9 95156.0
THE CONTACT FOR THE  68 ROTATION IS AT  8 60143.0
THE CONTACT FOR THE  69 ROTATION IS AT  7 60126.0
 THE MULTIPLE MINIMUMS ARE
     8   60      8    65
THE CONTACT FOR THE  70 ROTATION IS AT  8 65109.0
THE CONTACT FOR THE  71 ROTATION IS AT  8 60 93.0
THE CONTACT FOR THE  72 ROTATION IS AT  8 65 76.0
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Computer Output
Tibial Coordinates

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THE CONTACT FOR THE   0 ROTATION IS AT  8 65 76.0
THE CONTACT FOR THE   1 ROTATION IS AT  8 65 93.0
THE CONTACT FOR THE   2 ROTATION IS AT  8 75109.0
THE CONTACT FOR THE   3 ROTATION IS AT  7 75126.0
 THE MULTIPLE MINIMUMS ARE
     8   75      8   80
THE CONTACT FOR THE   4 ROTATION IS AT  8 80143.0
THE CONTACT FOR THE   5 ROTATION IS AT  9120156.0
THE CONTACT FOR THE   6 ROTATION IS AT  9120111.0
THE CONTACT FOR THE   7 ROTATION IS AT  9120 81.0
THE CONTACT FOR THE   8 ROTATION IS AT  9120 66.0
THE CONTACT FOR THE   9 ROTATION IS AT  9120 46.0
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THE CONTACT FOR THE  45 ROTATION IS AT  8295 13.0
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THE CONTACT FOR THE  68 ROTATION IS AT  8  45 26.0
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THE CONTACT FOR THE  70 ROTATION IS AT  8  55 61.0
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'HE CONTACT FOR THE  72 ROTATION IS AT  8  65 76.0
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